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Uncovering Topological Structures in Unstructured Data

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Final Report

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This research project aims to examine topological structures of scanned point-cloud data. It has two stages. In the first stage, we analyzed scan data and extracted topologically critical points. We used these critical points to enhance the robustness of slicing scan data in additive manufacturing. In the second stage, we focused on how to analyze scan data of a population of objects. In this context, we discovered novel ways of computing covariance matrix of shape population and developed methods for optimizing correspondence across a shape population.

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Final Performance Report

Uncovering Topological Structures in Unstructured Data (Grant FA9550-12-1-0206)

Xiaoping Qian

This research project aims to examine topological structures of scanned point-cloud data. It has two stages. In the first stage, we analyzed scan data and extracted topologically critical points. We used these critical points to enhance the robustness of slicing scan data in additive manufacturing.

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Two Ph.D. students, Kang Li and Xilu Wang, have participated in this research project. Kang Li has completed his Ph.D. dissertation [1]. Xilu Wang has publication pending.

In the past year, the following conference publication has received the ASME IDETC/CIE Prakash Krishnaswami CAPPD Best Paper Award:

- Li, K., Qian, X., Martin, C., and Sun, W., "Toward patient-specific computational study of aortic diseases : a population based shape modeling approach," ASME 2014 International Design and Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2014), Buffalo, NY, August 17-20, 2014. **(ASME CIE Division Prakash Krishnaswami CAPPD Best Paper)**

Specific research constructions are detailed as follows.

1 Direct Geometry Processing for Telefabrication

This paper [2] presents a new approach for telefabrication where a physical object is scanned in one location and fabricated in another location. This approach integrates three-dimensional (3D) scanning, geometric processing of scanned data, and additive manufacturing (AM) technologies. In this paper, we focus on a set of direct geometric processing techniques that enable the telefabrication. In this approach, 3D scan data are directly sliced into layer-wise contours. Sacrificial supports are generated directly from the contours and digital mask images of the objects and the supports for stereolithography apparatus (SLA) processes are then automatically generated. The salient feature of this approach is that it does not involve any intermediate geometric models such as STL, polygons, or nonuniform rational B-splines (NURBS) that are otherwise commonly used in prevalent approaches. The experimental results on a set of objects fabricated on several SLA machines confirm the effectiveness of the approach in faithfully telefabricating physical objects.

2 Direct Diffeomorphic Reparameterization for Correspondence Optimization in Statistical Shape Modeling

In this work [3], we propose an efficient optimization approach for obtaining shape correspondence across a group of objects for statistical shape modeling. With each shape represented in a B-spline based parametric form, the correspondence across the shape population is cast as an issue of seeking a reparametrization for each shape so that a quality measure of the resulting shape correspondence across the group is optimized. The quality measure is the description length of the covariance matrix of the shape population, with landmarks sampled on each shape. The movement of landmarks on each B-spline shape is controlled by the reparameterization of the B-spline shape. The reparameterization itself is also represented with B-splines and B-spline coefficients are used as optimization parameters. We have developed formulations for ensuring the bijectivity of the reparameterization. A gradient-based optimization approach is developed, including techniques such as constraint aggregation and adjoint senstivity for efficient, direct diffeomorphic reparameterization of landmarks to improve the group-wise shape correspondence. Numerical experiments on both synthetic and real 2D and 3D data sets demonstrate the efficiency and effectiveness of the proposed approach.

3 Toward patient-specific computational study of aortic diseases: a population based shape modeling approach

Patient-specific computational study of aortic disease provides a powerful means for diagnosis and pre-operative planning. However, creating patient-specific computational models can be time-consuming due to the fact that anatomical geometries extracted from clinical imaging data are often incomplete and noisy. This paper [4] presents an approach for constructing statistical shape models (SSMs) for aortic surfaces with the eventual goal of mapping the mean aorta geometries to raw surface data obtained from the clinical images for each new patient so that patient-specific models can be automatically constructed.

The input aortic models in this study come in the form of triangle meshes generated from CT scans on 6 patients. Statistical models with modes that characterize the variation pattern are found after optimizing the group-wise correspondence across the aorta training set. We use the direct reparametrization approach to efficiently manipulate shape correspondence. We use B-spline based differentiable shape representation for the training set and use the adjoint method for deriving analytical gradients in a gradient based approach for manipulating the shape correspondence to minimize the description length of the resulting SSM. Our numerical result shows that the evaluation measures of the optimized statistical model have been significantly enhanced.

4 Covariance matrix of a shape population: A tale on spline setting

Computing the covariance matrix of a population of shapes is essential for establishing shape correspondence, identifying shape variation across the population, and building statistical shape models. The covariance matrix is usually computed from a discrete set of points (a.k.a. landmarks) sampled on each shape. The distribution and density of the sampled points thus greatly influence the covariance matrix and its spectral decomposition. To understand and overcome this dependency on point sampling, in this paper [5], we develop accurate and efficient methods for directly computing continuous formulations of the covariance matrix. We adopt B-splines both as a shape representation and as a form of reparameterization. We apply B-splines into two continuous formulations for computing the covariance matrix of shapes. We develop both analytical and efficient numerical methods for computing such matrices. In both formulations, the covariance matrix from the corresponding numerical approximation converges to the matrix from the continuous formulations when the number of sampled points in each shape becomes sufficiently large. Their applications in optimizing shape correspondence by minimizing the description length of a set of shapes are presented.

References

[1] Kang Li. *Direct Diffeomorphic Reparameterization for Correspondence Optimization in Statistical Shape Modeling*. Ph.d. Thesis, Illinois Institute of Technology, 2015.

[2] Yong Chen, Kang Li, and Xiaoping Qian. Direct geometry processing for tele-fabrication. *ASME Journal of Computering and Information Science in Engineering*, 13(4):041002, 2013.

[3] Kang Li and Xiaoping Qian. Direct diffeomorphic reparameterization for correspondence optimization in statistical shape modeling. *Computer-Aided Design*, 64:33 –54, 2015.

[4] Kang Li, Xiaoping Qian, Caitlin Martin, and Wei Sun. Toward patient-specific computational study of aortic diseases : a population based shape modeling approach. In *Proceedings of the ASME 2014 International Design Engineering Technical Conferences, Buffalo, NY*, 2014.

[5] Kang Li and Xiaoping Qian. Covariance matrix of a shape population: a tale on spline setting. *Computers & Graphics*, 47:89–104, 2015.

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Abstract

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